ANOTHER (RE)VIEW OF LUNAR BASALTIC MAGMATISM
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INTRODUCTION

Early perceptions of lunar basaltic magmatism were that it was far less complicated than its terrestrial analog. However, over twenty years of lunar research has defined much more complex scenarios. End-member mare basalt generating models developed over the years include (A) partial melting of a primitive mantle source [1,2], (B) assimilation [3], (C) partial melting of a processed cumulate mantle source [4, 5], and (D) partial melting of a hybrid mantle source [6,7]. Superimposed on these melt generating processes are a number of possible secondary magmatic processes, such as fractional crystallization, AFC, and liquid immiscibility. This presentation emphasizes the generation of basaltic magmas in the lunar mantle.

Mare basalts comprise less than 1% of the lunar crust [8]. Assuming 35% partial melting (other models suggest less than 20% partial melting) less than 2% of the lunar mantle was involved in the partial melting events that produced all the basalt flows throughout lunar history. Compared to their terrestrial analogs, mare basalts show an incredible range in compositions. Early basalt studies differentiated high Ti basalt-glasses, low Ti basalt-glasses, and very low Ti basalt-glasses. Individual fractionation trajectories have been distinguished within these groups. Later studies have identified aluminous basalts [9, 10, 11], very high potassium aluminous basalts [9,11,12], and a wide compositional range of picritic volcanic glasses [13]. Partial melting models must address these wide major element compositional ranges and relationships among these basalt types.

CONNECTION BETWEEN PICRITIC GLASSES AND MARE BASALTS

Lunar picritic magmas (glasses) and crystalline mare basalts are products of basalt generation processes in the lunar mantle. As such, it is fundamental to our understanding of mare basalt petrogenesis to not only comprehend the generation of each, but to also grasp the linkages between these magmas. The glasses tend to have higher Mg/(Mg+Fe) than crystalline mare basalts [13]; and therefore, a logical assumption is that the crystalline basalts were derived from primary magmas with compositions similar to the picritic glasses. However, liquid lines of descent for major and trace elements suggest that most mare basalts are not directly derived by simple low-pressure fractionation from parental melts with compositions identical to that of the picritic glasses [14, 15, 16]. Numerous lines of evidence may be interpreted as suggesting the picritic glasses and mare basalts represent magma generation from two distinct sources: (a) lack of low pressure fractionation linkages between glasses and basalts, (b) differences in experimentally determined multiple saturation depths, (c) volatile-rich source for the picritic glasses suggested by mode of eruptive mechanism (fire-fountaining) and U/Pb isotopic ratios [17, 18]. However, (a) may also be interpreted as indicating a sampling problem, whereas (b) may reflect the more derivative nature (via fractional crystallization) of the crystalline basalts (see below).

In any event, present data [15, 16, 19] indicates a heterogeneous mantle at depths of >300 km, capable upon melting of generating a wide spectrum of compositionally distinct picritic magmas (high-, low-Ti) with a range of incompatible trace element signatures (i.e., KREEP). The relationship between the picritic and basaltic magmas may reflect (A) derivation of most basalts from below 300 km as picritic magma. Mare basalts are derived from a volatile-poor, heterogeneous mantle source and are fractionated on their path to the lunar surface, while the picritic magma are derived from a volatile-rich, heterogeneous source and delivered to the lunar surface rapidly; or (B) picritic magma are derived from a deeper (>300 km), heterogeneous source than the mare basalts (<300 km). PROBLEMS: Are the sources for the mare basalts as heterogeneous as the picritic magma sources? What are the mechanisms for extensive mantle fractionation and heterogeneity? How can one distinguish between models (A) and (B)?

SOURCE FOR CRISTALLINE MARE BASALTS

Like the evidence from the picritic glasses, various studies have shown that the crystalline mare basalts were derived from source regions with dramatic (high-Ti to very low-Ti sources) to subtle compositional differences. As an example of the latter, Rhodes et al. [20], Beatty et al. [21], Nyquist et al. [22], Ryder [23], and Neal et al. [24] concluded that the high-Ti basalts from the A-11 and A-17 sites define at least 10 distinct batches of magma unaltered by fractional crystallization or partial melting. Using the empirical models of Longhi [14], we calculated liquid lines of descent for the picritic magmas and liquid lines of "ascent" for the crystalline mare basalts. Approximately 10-20% olivine fractionation is required to extend the most primitive crystalline mare basalts (i.e., 70215, 744275) into the picritic glass field. The existence of lunar picritic magmas (glasses) of compositions which at least approach these back calculated picrites and multiple saturation at low pressures of many of the most Mg-rich, high-Ti basalts [25] suggest many may have been derived from the fractionation of picritic parent magmas. These picritic parents for the crystalline basalts may have been derived at depths equivalent to that of the multiple saturation depth of the picrites glasses. Walker et al. [26], Kesson [25], and Kesson and Lindsley [27] implied that the most Mg-rich magmas of the crystalline basalt high-Ti suite were not a product of near surface fractionation. Therefore, 10-20% fractionation may have occurred in route to the lunar surface. If even the most Mg-rich members of the crystalline basalt suite are products of 10-20% fractional crystallization, estimates of melt segregation depths and trace element mantle inversion models based on the crystalline basalts may be inadequate. The empirically calculated picritic compositions and picrite
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POSSIBLE MODELS FOR MARE BASALT MAGMATISM

There are several possible models for the origin of mare basalts, which can be classified into two main groups: those that involve melting of a mantle source and those that involve mixing of different magma types.

- **Melting of a Mantle Source:** This model suggests that the mare basalts are produced by partial melting of a depleted mantle source. The melting process can be driven by the ascent of a mantle plume or by the addition of water to the mantle.

- **Mixing of Different Magma Types:** This model proposes that the mare basalts are formed by the mixing of two or more magma types, each with different properties. The mixing can occur in the magma chamber or during eruption.

In either case, the resulting magma is characterized by a unique combination of chemical and isotopic signatures.

**Summary:**

Our current understanding of the formation of mare basalts is still limited, and further studies are required to fully understand the complex processes involved in their formation.